



Colorimetric patterns of wood pellets and their relations with quality and energy parameters



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HIGHLIGHTS

- This study aims to verify the correlation between color and quality parameters of wood pellets.
- Result proved that color differences are perceptible by human eye.
- It is possible to observe good correlations between ash and CIE $L^*a^*b^*$ (pellet and GAS), RGB and HSV values.
- Sample lighter in color mainly clustered in the space where HHV, DU and densities have higher scores.
- Darker samples were dispersing in the opposite space dominated by higher ash and moisture contents.

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ABSTRACT

Color of wood pellets is mainly affected by the feedstock material used for their production and which composition and characteristic affect the final product quality. Pellets made from pure wood are light in color and have low ash content, while pellets made from different mixtures of wood and bark or foliage are generally darker and richer in minerals. This study aims to verify the correlation between color and quality parameters of wood pellets available on the Italian market. All the samples were analyzed following the procedures laid down by the European Norms (EN) on solid biofuels for moisture, ash, calorific value, durability, bulk and solid density. The acquisition of the images was done with two techniques: the CIE $L^*a^*b^*$ color space and RGB–HSV color spaces. Canonical correlation analysis (CCA) was performed with CIE- $L^*a^*b^*$, RGB and HSV separately showing for all the color components good degree of correlation with ash content of pellets. The PCA analysis on two principal components (total explained variance: 64.2%) showed a clear color gradient moving from good to medium or low quality parameters. This pattern is confirmed by the clustering of certified pellets in the region of lightest samples. The calculation of ΔE and ΔRGB showed a good discrimination level between whole pellets samples and their sawdust, and between ones with high and low ash content. The visual predictability of pellets quality on the basis of their color is however not so sharp when considering samples with similar colors. The industrial applicability of such methods for the evaluation of pellets quality is desirable for RGB methodologies that are less expensive and more reliable in working condition, given that specific color calibration is performed.

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1. Introduction

Wood pellets are one of the wider internationally spread biofuel commodities for energy production and their market is booming in

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Europe [1] mainly driven by the fairly low cost per energy unit and the European and National subsidy systems to achieve the 2020 targets. Nowadays the continuous increasing demand in wood pellets seems not to be totally met by the domestic production, not for technology limitation, but for shortage in primary resources and due to the competition with large power plants [2] and wood industry. Even if specific and accurate statistics for pellets sector are missing, the European market is dependent on importation [3] and the ENplus annual report underlines that the Italian import

Abbreviations

A	ash content	GAS	General Analysis Sample
a^*	color coordinate along the X axis red (+) to green (–)	HHV _{ar}	high heating value as received
AbDe	Norway spruce debarked stem	HHV _{daf}	high heating value on dry basis and ash free
AbSt	Norway spruce whole stem	HSV	hue, saturation, lightness (color space)
AbTr	Norway spruce whole tree	HV	heating value
b^*	color coordinate along the Y axis yellow (+) to blue (–)	ISO	International Organization for Standardization
BD	bulk density	L	length
CCA	canonical correlation analysis	L^*	lightness (color coordinate)
CCD	charge-coupled device	M	moisture content
CIE	Commission Internationale de l'Eclairage	m_b^{-3}	bulk cubic meter
CMOS	complementary metal-oxide-semiconductor	NIR	near-infrared
D	particle density	PCA	Principal Component Analysis
d.p.i	dots per inch	RGB	Red, Green, Blue (color space)
DU	mechanical durability	ROI	region of interest
EN	European Norm	sRGB	standard Red, Green, Blue (color space)
F	finer content	TPS	Thin Plate Spline
FaBr	beech branches	% _{ar}	percentage as received
FaSt	beech whole stem	Ø	diameter

of wood pellets from abroad (within EU-27, Canada, United States, South America and New Zealand) is actually filling the gap between the domestic production and consumption [4].

Compared with other biofuels, pellets have higher energy density, lower transportation and storage costs [5,6] and their regular shape allows the automation of feeding procedure in burning appliances [7]. These are some of the reasons why wood pellets have a wide diffusion on the biofuels market. Wood pellets final quality is affected by a series of different parameters, both deriving from intrinsic feedstock characteristics, and treatment or production conditions.

Raw materials properties affect pellets quality as soon as their constituents are found nearly unchanged in the final product. Tree species and wood provenance has been found to influence the pelletizing process [8], and the final pellet quality [9,10], especially if related with the sawdust particle size distribution and its content in fatty acids [11,12]. The total amount of ash in the biofuel is also related with tree species introduced in the blend of feedstock as different woods are characterized by different amount of unburnt residues [13].

The color of pellets made from pure wood sawdust, processing residues or debarked stems and shavings have generally lighter colors. The absence of bark results in lower ash contents compared with wood [14,15] but, on the other hand, in low mechanical properties, especially durability [16], that detects the proneness of pellet to disintegrate when exposed to mechanical stresses. This can result in higher fine particles content that affects pellets quality during transportation, storing, stove feeding and final burning [14]. Pellets produced from whole stems, including bark or mineral contaminants, are instead darker in color and usually their ash content is higher [17], lowering the content of energetic matter in the biofuel and the quality of the combustion behavior, to the point that pure bark pellets can be burnt only in large heating plants [14].

Storage conditions of raw material, that can modify the chemical constitution of wood, influence the mechanical compaction behavior of the sawdust. In particular the natural seasoning and low temperature drying results in more durable pellets compared with ones made from artificially and fast dried at high temperatures [14]. The exposure of raw material to high temperatures during drying changes both its chemical properties and external appearance affecting also the resulting pellet color [18,19]. Heat

exposure, in fact, modifies the wood structure and color in dependence of temperature and presence or absence of oxygen [20].

The moisture in the feedstock as bound water plays a key role in the formation of interparticles linkages. Moist feedstock results in weaker pellets, to the point that sawdust is no longer able to remain compacted after exiting the die channel. On the other hand, the moisture content, acting as lubricant, can affect positively the resulting pelletizing pressure and temperature [21], again influencing the final color result [17]. The optimal ranges for water content values are found to be 8–13% [9,14].

This variability in pellets quality parameters has stimulated many countries to develop specific standards and regulations in the attempt to set some baselines for production, storage and distribution of wood pellets [7]. The national standardization process has resulted, by the end of 2012, to the publication of some harmonized EN (European Norms) regulating pellets quality parameters and classes.

The experience developed in the study of the wood pellet sector for residential heating has shown that a strong emphasis is put on the color of pellets due to the fact that the market is very reactive to this parameter, and this is verified considering that dark color pellets have a lower commercial value than light wood pellets [17] (the so called “white pellets”), especially for residential applications. In fact consumers tend to associate the darker color with the contamination of raw materials with impurities such as bark, which high ash content is reflected in the final pellet quality.

Even if color is not a parameter for grading pellets quality as defined by the European and International Norms (EN–ISO), the market trend and the consumer choice are strongly affected by this parameter that is the only one directly verifiable at first sight [22,23]. On the other side, this consideration is not supported by scientific studies and a lack of knowledge regarding color and quality applied to pellet properties is registered. Very little literature is available (mainly on change in color of feedstock that underwent thermal drying) and no clear relationships among pellet characteristics and its color have been proved.

Each color depends on the type of emission source that irradiates an object, as well as on the physical properties of the object itself (which reflects the radiation consequently detected by the sensor), and finally on the in-between medium (e.g., air or water) [24]. Generally, the color spaces applied for product classification are the standard RGB (sRGB; red, green, blue) and CIE $L^*a^*b^*$. sRGB

can be obtained rapidly using computer vision systems being the color of a pixel of a digital image expressed by three coordinates (sRGB) [25,26]. However, the RGB model is device-dependent and not identical to the intensities of the CIE system which therefore is spectral based measurement in the range 400–700 nm and could be considered as device-independent. Outputs signals are generated by the camera sensors (e.g., CCD or CMOS), but the rendering is device dependent, since the range of colors varies according to the display device specifications [27]. In order to overcome this problem, sRGB values are often transformed to other color spaces such $L^*a^*b^*$. Moreover, even the result of such transformation is device dependent [28]. Researches show that color has been successfully used in classifying a variety of products mainly in the food and industrial sectors [29–34]; to improve the success rate of detecting color-based industrial products features, color vision algorithms must be coupled with accurate color calibration methods. Another technique, used in the industrial product processing, is the Near-infrared (NIR) spectroscopy that has been already tested to study the species composition in wood pellets [12] or to detect the presence of specific chemicals [35]. The application of this technology is already well known and broadly applied to online estimation of moisture content in woody materials [36,37].

The current work investigated the color characteristics of some commercial and control pellets with the aim to detect if quality parameters are effectively related with colorimetric values and image patterns and finally clarify the possibility to verify the consumer pellet choice based on visual evaluation.

2. Materials and methods

2.1. Pellets characterization

The sampling campaign was based on the random selection of 51 pellet bags (15 kg each) collected from 25 Italian retailers and producers regardless to their provenience, cost or commercial name. The sample supplier was not told about the scientific scope of the work to avoid any kind of positive selection of the material prior the delivery. This procedure has ensured that no influence of the production parameters affecting the final quality of the pellet could occur due to the consciousness of the producer about the study going on.

All the possible information about the origin, source and raw material used, certification and measured parameters were recorded. Each sample was given a unique ID number and transferred to an anonymous plastic bag for further analysis at the Bio-fuel Laboratory (Lab ABC) of the University of Padua (Italy). The quality analysis was done based on the classes proposed by the EN 14961-1, which delegates to a number of other satellite norms the role to specify each parameter determination procedure [38]. The fines content (F), mechanical durability (DU), moisture content (M), bulk density (BD), particle density (D), diameter ($\emptyset$), length (L), ash content (A), calorific value (HV), were determined with the required number of replications and level of precision (repeatability and reproducibility). For further analysis and to define the quality class of each sample the EN 14961-2 was applied [39]. Moreover five reference pellets types, specifically produced by the Lab ABC for the scope of this work, were sampled and analyzed. They were produced under the same condition of seasoning, production and post treatment. Two species were used: Norway spruce (*Picea abies* Karst) and beech (*Fagus sylvatica* L). For the former, whole tree (AbTr), whole stem (AbSt) and debarked stem (AbDe) were collected. For the latter whole stem (FaSt) and branches (FaBr) were collected. The feedstock types were chosen considering that residual or non-commercial timber from these two species is mainly left on the ground or harvested for low valuable utilizations. The high

demand of biofuels can create a good supply opportunity also for these base materials.

The percentage of dust and fines (F), determined by weighting and sieving the sample as stated in the EN 15149 [40], is correlated with the mechanical properties of the pellet, with its tendency to disintegrate under stress [5] and to the dust reduction system efficiency (sieves and aspirators). Once the pellets have been sieved the mechanical durability test was performed on 500 g subsamples on 3 repetitions according to the [41]. The percentage of pellets remained integral compared to the initial subsample weight gives the DU value.

The moisture content (M) was determined following the EN 14774-1 by placing 3 subsamples of each pellets type in a ventilated oven at 105 °C until constancy in weight is reached [42]. The results were expressed in percentage on wet basis as received ($\%_{ar}$).

The bulk density (BD) was determined by the mean of a 5 l steel container which properties are stated in EN 15103 [43]. Firstly it was overfilled and then the material was compacted by dropping the container from 15 cm on a hard surface and finally refilled and leveled to the top. The final weight related to a volume of one cubic meter gives the bulk density value expressed in kg m^{-3} .

The density (D) of single pellets was determined by the relationship between the mass and the solid volume of a piece. Both mass and volume of a group of pellets were determined as stated in EN 15150 [44]. The volume was estimated through the principle that the buoyancy of a body is equal to the weight of the displaced fluid volume. The apparent loss in weight between a measurement in air and a subsequent measurement in water marks its buoyancy. The volume of the pellets was calculated given the density of the immersion liquid at controlled room temperature (20 °C). The result is given in g cm^{-3} . This methodology is not devoid of errors, mainly caused by the rapid uptake of water from pellets. Despite this it has been proved to be the most reliable one, compared with hydrostatic or stereometric procedures [45].

The dimensions were measured by the mean of a caliper recording diameters and length in mm.

A subsample was prepared for further analysis using a laboratory cutting mill to reduce the particle size distribution to a nominal top size of 1 mm as required by the reference standard (General Analysis Sample – GAS). The nominal top size is intended as the aperture size of the sieve used for determining the particle size distribution through which at least 95% by mass of the material passes [46].

The ash content (A) was determined following the EN 14775 and weighting a portion of GAS before and after its complete combustion in a muffle oven over a period of 5 h under fixed temperature conditions [47]. The results are reported on dry basis ($\%_{dry}$).

The calorific value was determined according to the EN 14918 using the IKA C-200 calorimeter which gives the result as the high heating value as received (HHV_{ar}) [48]. Further calculation converted the HHV_{ar} into HHV_{daf} (on dry basis and ash free). Wherever not specified in this paper with HHV we refer to HHV_{daf} .

2.2. Color analysis

Color measurement was performed with two different kinds of approaches. The first method, applied on whole pellets samples and GAS, is based on CIE (*Commission Internationale de l'Eclairage*) L^* (lightness) a^* [along the X axis red (+) to green (–)] b^* [along the Y axis yellow (+) to blue (–)] color space [49], the second is based on RGB and HSV color spaces.

CIE $L^*a^*b^*$ colorimetric information were acquired using an imaging spectrometer (Spectral Scanner, v. 1.4.1, DV Optics, Padova, Italy) which digitized images (Fig. 1) ranging from 400 to 790 nm (step 5 nm) following details and settings exposed by



Fig. 1. Image acquired by the VIS–NIR spectral scanner (range 400–790 nm) on whole pellets (lower sample) and GAS (upper sample).

[50]. Each frame contained the line pixels in one dimension (spatial axis) and the spectral pixels in the other dimension (spectral axis), providing full spectral information for each pixel line. The reconstruction of the entire hyperspectral image of the sample was performed by scanning the sample line by line as the transportation plate moved it through the field of view of the sensor. The resolution of the line image was 700 pixels per line for 500 lines. The system was operated in a dark laboratory to minimize interference from ambient light, and the system was calibrated using black and white references. The spectral scanner acquired images of single pellets and GAS. Mean CIE $L^*a^*b^*$ values (3 values) of 5 region of interest (ROI) were used for each pellet sample.

RGB and HSV color information of single pellets were acquired through a professional high resolution scanner (600 d.p.i.). Images of more than 100 pellets for each run (Fig. 2) were acquired together with a GretagMacbeth ColorChecker 24 color patches standard. In order to standardize the RGB color, images were calibrated using the Thin Plate Spline interpolation algorithm (TPS 3D) [51]. Inside the calibrated images each pellet were outlined from the dark background automatically. Image binarization was performed by means of fixed threshold value applied on each RGB channel respectively ($R = 25$, $G = 25$, $B = 25$). Mean RGB and HSV



Fig. 2. Image of pellets acquired with a high-resolution scanner (600 d.p.i.), the 24 color patches standard is used for the calibration. The ruler is for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

values of all the pellets belonging to the same sample were used in the further statistical analysis.

Differences in terms of CIE $L^*a^*b^*$ values between pellets and GAS were estimated using the ΔE calculation respectively to observe whether same color results can be obtained from different sample form (values lower than 3). The ΔE , and further on the ΔRGB , represent the Euclidean distance between two colorimetric patches in the color space, CIE L^*a^*b or RGB respectively.

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{\frac{1}{2}} \quad (1)$$

$$\Delta RGB = [(\Delta R^*)^2 + (\Delta G^*)^2 + (\Delta B^*)^2]^{\frac{1}{2}} \quad (2)$$

ΔE and ΔRGB were calculated for samples of whole pellets and GAS having respectively high and low ash content values, to define the possibility for the human eye to detect some differences among different pellets types and qualities based on colorimetric characteristics [52,53].

2.3. Statistical evaluation

Canonical correlation analysis (CCA) was used to observe the degree of correlation of ash with CIE L^*a^*b , RGB and HSV separately. CCA is a way of measuring the linear relationship between two multidimensional variables. It finds two bases, one for each variable, that are optimal with respect to correlations and, at the same time, it finds the corresponding correlations. Canonical correlations are invariant with respect to affine transformations of the variables. This is the most important difference between CCA and ordinary correlation analysis which highly depends on the basis in which the variables are described [54]. Canonical correlation coefficients representing the degree of correlation between ash and the color coordinates were reported together with their significance (χ^2 test). To investigate the single relationship between each colorimetric variable and ash content, the Pearson linear correlation coefficient was reported.

In this study the Principal Component Analysis (PCA) was performed to verify the influence of quality parameters on the overall sample classification and to relate those with sample color (RGB). The PCA is an ordination technique based on a projection method which allows the display of information in a data matrix considering the influence of each in a limited number of components expressed as linear function of the original ones. The data matrix, consisting of the quality pellet parameters for all the variables, contains a large amount of information partially hidden because the differences among samples are complex and not of easy representation. The first two (i.e., the most informative) principal components (PC) were selected. The analysis was done considering the loading of six parameters: D , A , M , DU , HHV and BD on each PC. The results allow to visualize the samples according with their scores. Similar scores along a component detect similarities for variables with a high loading for that component.

3. Results

To observe if differences in terms of CIE $L^*a^*b^*$ between whole pellets and GAS were perceptible by human eye, mean ΔE were calculated. Human eye perceives clearly color differences for ΔE values greater than 3 [55]. They resulted to be 8.0 ± 3.9 . This result proved that these slight differences are perceptible by human eye as they resulted to be significantly higher than 3 (one sample t test, $p < 0.0001$).

In Table 1 the summary of the CCA results is reported. It is possible to observe good correlations between ash and CIE $L^*a^*b^*$ (pellet and GAS), RGB and HSV values. In particular GAS $L^*a^*b^*$

Table 1

Summary of the results of the canonical correlation analysis (CCA).

	Canonical correlation coefficient	CCA coefficient significance	Pearson $L^*/R/H$ vs ASH	Pearson $a^*/G/S$ vs ASH	Pearson $b^*/B/V$ vs ASH
Pellet–CIE $L^*a^*b^*$	0.70	<0.0001	–0.67	–0.19	–0.61
GAS–CIE $L^*a^*b^*$	0.78	<0.0001	–0.73	0.09	–0.64
Pellet–RGB	0.70	<0.0001	–0.69	–0.67	–0.63
Pellet–HSV	0.72	<0.0001	0.53	–0.20	–0.69

	CIE $L^*a^*b^*$ GAS	CIE $L^*a^*b^*$ pellet	RGB pellet
High ash content			
Low ash content			
	ΔE	ΔE	ΔRGB
	30.3	36.0	104.6

Fig. 3. Colorimetric patches representing the CIE $L^*a^*b^*$ (GAS and pellet) and RGB mean values of the 4 pellet samples having respectively higher (>3.85) and lower (<0.36) ash values.

values are highly correlated with ash (0.78). The single colorimetric components of the color space are all negatively and highly correlated with ASH a part hue (highly positively correlated) and saturation (low negatively correlated) of the HSV space and a^* (low positively correlated) of the CIE $L^*a^*b^*$ space.

Fig. 3 reports the colorimetric representations of CIE $L^*a^*b^*$ on GAS and on pellets and RGB mean values (only on pellets) for the 4 samples having respectively highest (>3.85%) and lowest (<0.36%) ash content percentages values. ΔE and ΔRGB values between these two group mean values are respectively 30.3 and 104.6. These high delta values are perceptible by human eye since they are higher than the reference values 3 (ΔE) and 6 (ΔRGB) respectively. It demonstrates that high ash concentrations are likely to be related with darker colors regardless it is measured on GAS or whole pellets sample.

Fig. 4 represents the PCA ordination on the first two (i.e., the most informative) PCs. The position of each variable defines its

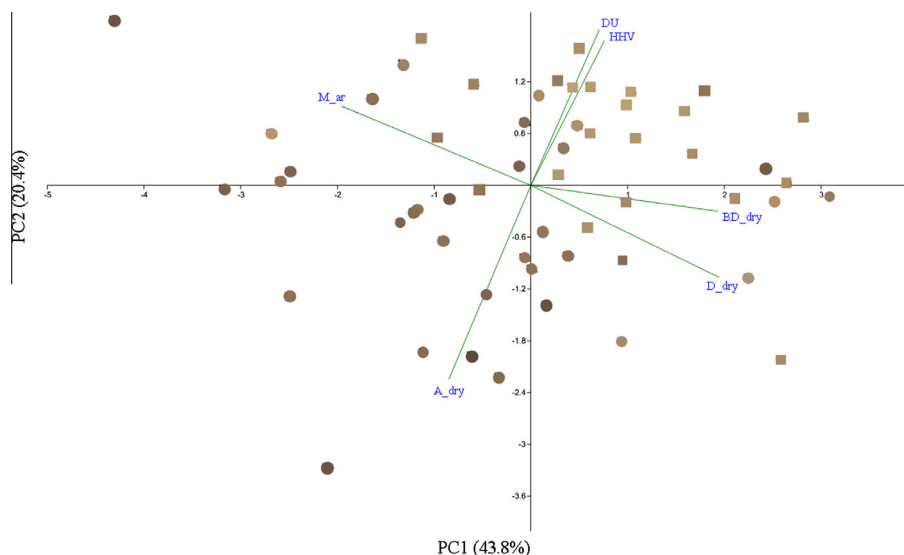
score along each principal component. The closer is a variable vector to an axis, the higher is the contribution on that PC. A sample positioned in a specific variable direction is highly influenced by that variable. The total variance explained by the first two axes is 64.2%, where 43.8% is explained by the first PC, and 20.4% is explained by the second PC.

For each sample a dot locates its position in the graph with respect to the first two PC, while the color of the dot itself represents the average RGB value for that sample at its initial moisture condition (referred as received) measured during the image analysis.

Along the first PC axis the variables A , D and BD give a negative contribution (i.e. the variables decrease their values when the PC1 scores increase). On the contrary DU and HHV variables give a higher and positive contribution to the samples ordination (and also along the second one), while, M is less strong. Along the second PC axis the major contributors are M (negative), BD and D (positive). Visually it can be noticed that the majority of the darkest samples are located in the third quadrant, where A values have higher load, while the lightest ones are mainly aggregated in the first quadrant where HHV and DU have higher loads. In the second and fourth quadrants the samples with intermediate colors are located. In these regions the loadings and significance of the representative variables (M , D and BD) are lower and no clear relationships can be detected.

The presence of some light brown samples in the second quadrant is mainly driven by the influence of the moisture content that makes colors darker. This factor is averted for the other parameters as they are referred on dry basis.

It can be noticed in Fig. 4 that a dense cluster of certified samples (squares) is aggregated in the first quadrant, with few cases of samples trespassing to the second and fourth. Only one sample is

**Fig. 4.** Graphical layout of the PCA results. The x-axis represents the PC1 while the y-axis the PC2. The value in brackets represents the variance explained by that PC (total variance explained: 64.2%). Dot color represents the RGB average measured for that sample. Squares locate the position of certified samples. The position of each variable (M , DU , HHV , BD , D , A) detects its loading for the two PC detected (graph axis) and gives a reference for the results interpretation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

located further from the cluster on the fourth quadrant even if it was declared as certified. This is due to its abnormal values of M (very low) and A (very high). A second group of samples, mainly clustered around the origin of the axis, is represented by the five reference pellets types (AbDe, AbSt, AbTr, FaSt, FaBr). Both the beech samples are located in the negative sector of the first PC due to their relatively high ash content and low values of HHV, while, on the contrary, AbSt and AbTr are located in the opposite side. The outer position of AbDe, close to the load value of D and BD along the first PC, is due to its high D and BD, while it has the lowest value of HHV among spruce samples and the lowest DU value among all, confirming that pure wood pellets often results in low mechanical and energetic properties.

4. Discussion

The explanation why the final appearance of some pellets is darker than some others could not be found only in their constituent formula. It has been said how the outer color of pellets is affected by a number of factors such as moisture content, feedstock treatment and production parameters.

The color analysis revealed a perceptible difference between the CIE $L^*a^*b^*$ of pellets (the outer surface) and GAS (ground pellets) that is proven to be greater than 3. The reasons for that are twofold. The cylindrical form of pellets caused the presence in the image taken with VIS–NIR of areas of reflection and areas of shadow because their convex surfaces did not reflect the light evenly when illuminated at 45° (device dependent). This effect is emphasized by the lucid pattern of the outer pellet layer due to the glass transition (softening point) of lignin and hemicelluloses caused by the pelletizing temperatures that enhances the bonding effect of wood particles [15]. Secondly thermal shock to which wood is subjected during the production makes it generally darker in color with lower brightening and values of L^* [56] and different hygroscopicity [19]. The contact with the hot die at high friction forces during extrusion causes the external layer darkening to be enhanced than the inside. This is confirmed by [17] who have found that the L^* values of the ground raw material compared with the pellets made out from the same biomass are higher and result in lighter colors. In the same work, to avoid the affection of the color response by the moisture content, all the samples were oven dried. As the aim of this study is to prove the relation between visual appearances of pellets with their quality, the water content of each sample was determined and included (not discarded) from the analysis.

Significant correlations (CCA) were observed between color and ash content for CIE L^*a^*b (GAS and pellet) and RGB–HSV (pellet). The direction of the correlation has showed that higher values of ash are mostly associated with darker colors. These differences, detected by the device, are visually perceptible ($\Delta E - \Delta RGB$) when considering the color of samples at the extremes of ash contents distribution (highest and lowest). On the other hand when intermediate ash content pellets are to be visually evaluated by the consumer, color similarities can be difficult to be perceived at first sight. The procedure is enhanced when the evaluation is done comparing two samples near to each other because the ability to detect color differences is higher if done through comparisons of two or more samples instead of estimating single sample absolute values.

For this reason the capability of the consumer to define the quality of pellets only referring to their external color still has a wide degree of uncertainty.

The PCA underlined the influence of the measured parameters, in addition to the ash content, in the quality grading of pellets. Good pellets are those able to undergo mechanical stresses and are converted in high energy when burnt. To achieve this, low moisture contents, high densities and high heating values are

required. Complementarily the content in minerals, resulting in ashes, is to be avoided as it reduces the energy content of pellets and can affect negatively the combustion [57–59]. The distribution pattern of all the samples has confirmed a strong relation of RGB mean values with their overall quality and has also outlined that pellets declared as certified by the producers have generally good quality and lighter colors. This is in good agreement with what it was expected from the previous analysis.

Systems based on the spectral measure of the color ($L^*a^*b^*$) are expensive, complex and require high utilization standard, as their sensitivity to the environment conditions (mainly lighting) is high. Furthermore they do not give any appreciable advantage to the estimation of the quality parameters if compared with the other systems studied. The device used for the study, which is an imaging spectrometer, provides a better appreciation of the color of individual pellet net of shadows and steric geometric characteristics of pellets compared to the standard colorimeters with integration of area.

On the other hand the RGB imaging system, once properly calibrated [51] is proven to be a convenient alternative when applied for color analysis. These systems are not only cheaper and more efficient than the previous ones, but they also can be easily implemented directly on production processing lines.

Spectroscopy and color measurement has been used in a large variety of applied sciences and their utilization is well developed and robust. On the other hand the biomass sector is seeking for new application for detecting quality parameters online and continuously. The advantages connected with the fast estimation of moisture content, ash content and calorific value are mostly not compensated by the high initial investment of purchasing all the devices for internal analysis set up. Instruments for the qualification of product quality directly online are nowadays easily available and implementable on the production process [17].

5. Conclusions

The relationship between colorimetric characteristics of wood pellets for energy purposes and their quality parameters was investigated. High degrees of correlation were found between CIE L^*a^*b , RGB and HSV separately and values of ash contents, which has been considered to be the most appropriate indicator as it is the biggest concern among final consumers in domestic appliances. The direction of the correlation was proved to be constant and darker pellets are more prone to have higher ash content. The same results were obtained analyzing the pellets as they are or grinding them to a nominal top size of 1 mm (GAS). Moreover the mean ΔE between pellets and the respective GAS were detected to be appreciable by human eyes as they were all higher than 3. This is due to the modification that wood particles and fiber constituent (lining and cellulose) undergo during the pelletizing phase and the different moisture condition of the inside of the pellet compared with the outer layer. ΔE and ΔRGB calculated between the 4 samples with highest and lowest ash content showed results fairly high, confirming that the direction of change of ash and colors is the same, and visually appreciable. This is not confirmed for sample with color similar to each other, where the predictability of their quality is less certain. Samples have shown a clear distribution along the two PC considering mechanical (DU), physical (A , M , BD, D) and energetic (HHV) variables. The same general pattern was verified for pellets sold as certified products that are supposed to have higher quality properties. Sample lighter in color mainly clustered in the space where HHV, DU and densities have higher scores. On the other hand darker samples were dispersing in the opposite space dominated by higher ash and moisture contents.

The application of such methodology directly to the industry seems to be possible considering some developing factors:

- Vis NIR spectroscopy, which is fairly expensive, need specific work environment and can be highly affected by the lighting conditions and the stereometrics of the objects analyzed.
- RGB imaging systems are cheaper and lead to reliable results similar to the previous ones.
- RGB imaging systems, if duly implemented, give faster and less expensive responses than the traditional quality analysis done in a laboratory following the EN standards. This allows to adopt such methodology to detect differences online.

Appropriate color calibration has to be applied to avoid errors.

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